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Radio Transients, Stellar End Products, and SETI Working Group Report

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14. ABSTRACT This working group (WG) has identified the following projects as forefront science to be pursued with the Square Kilometer Array (SKA) and which drive specifications of the SKA. In particular, pulsars, transients, and some Search for Extraterrestrial Intelligence (SETI) activities require observing modes that differ markedly from those designed for imaging modes of sources that do not vary with time. Therefore, care must be taken in the conceptual and design phases of the SKA to ensure that science in these areas can be undertaken and optimized. As a notable historical example, we point out that the original discovery of pulsars involved an <i>array</i> optimized for detecting relatively fast (at that time) scintillations. By comparison, the Very Large Array (VLA) has not discovered any new pulsars, in part because its design has hampered the analysis of short timescale signals. Consequently, the vast majority of radio pulsar discoveries has been made with single-dish antennas. This should not be the case with the SKA!					
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Radio Transients, Stellar End Products, and SETI Working Group Report

1 Science Projects

This WG has identified the following projects as forefront science to be pursued with the SKA and which drive specifications of the SKA. In particular, pulsars, transients, and some SETI require observing modes that differ markedly from those designed for imaging modes of sources that do not vary with time. Therefore, care must be taken in the conceptual and design phases of the SKA to ensure that science in these areas can be undertaken and optimized. As a notable historical example, we point out that the original discovery of pulsars involved an *array* optimized for detecting relatively fast (at that time) scintillations. By comparison, the VLA has not discovered any new pulsars, in part because its design has hampered the analysis of short timescale signals. Consequently, the vast majority of radio pulsar discoveries has been made with single-dish antennas. This should not be the case with the SKA!

1.1 Level 1

Radio Transient Universe The SKA will produce the first, unbiased survey of the variable radio sky at centimeter wavelengths. A useful comparison is to gamma-ray bursts (GRBs), which were detected only because a previously unexplored region of parameter space for gamma-ray observations (namely all-sky, high time resolution observations) were conducted. After 30 yr of mystery, GRBs may now prove to be useful probes of the star formation history of the Universe and the intergalactic medium. Based on the known populations of radio transient sources, such a survey could reveal populations of radio pulsars in nearby galaxies (via the emission of giant pulses like those of the Crab pulsars), possibly as distant as the Virgo Cluster. A byproduct of the detection of such pulsars would be direct detection of the ionized local intergalactic medium. In turn, this would allow study of the bulk of the baryons in the local Universe. Such a survey could also reveal microquasars throughout the Local Super-cluster. We emphasize, however, that these predictions are based on the known populations of transient sources. The greatest return from such a survey will (should!) be the detection of currently unknown populations of sources.

Galactic Pulsar Census Radio pulsars provide unparalleled probes of fundamental physics, and their signals provide unique diagnostics of intervening media. For example, their pulse periods, particularly those near 1 ms, constrain the nuclear equation of state; discovery of a pulsar

with a pulse period below 1 ms would provide even tighter constraints. Neutron star-neutron star binaries have provided indirect detection of gravitational waves; discovery of neutron star-neutron star binaries in tighter orbits or, particularly, black hole-neutron star binaries would enable more precise tests of strong-field gravity. A timing array of millisecond pulsars could be used to search for gravitational waves with frequencies inaccessible to LIGO and LISA.

The current sample of Galactic radio pulsars has been used to produce a low-resolution tomographic map of the Galactic ionized interstellar medium. To produce a detailed map—including the electron density and magnetic field and their fluctuations on a variety of length scales—the largest possible pulsar sample is required. For mapping the magnetic field, a large number of polarized extragalactic sources will also contribute to the analysis, but the pulsar sample is absolutely required for a three-dimensional map. (Note that this outcome of a complete Galactic census ties into discussion and goals from The Milky Way and Local Galaxies Working Group). Concordantly, objects that allow tests of fundamental physics tend to be rare, comprising only a small fraction of the pulsar population (e.g. $\lesssim 1\%$). In order to find rare objects that will push our abilities further, we also need a large, total pulsar yield.

Estimates of the total number of active radio pulsars in the Galaxy are of order 100 000, with perhaps 20% of them beamed toward the Earth. Yet, the current (incomplete) census of Galactic radio pulsars numbers only 1500. Figure 1 shows that the SKA will increase the number of detected pulsars by an order of magnitude and will approach detecting all pulsars in the Galaxy beamed toward the Earth. With an order of magnitude more sources, and the sensitivity and timing precision provided by the SKA, pulsar astronomy will not be a mere continuation of its successes but will even reach a completely new quality of science.

SETI Even without detailed knowledge of the luminosity function of ETI transmitters nor of ETI signal structure, it is almost self-evident that the SKA will allow unprecedented characterization of the ETI sky. Sensitivity of course allows probing to greater distances for a given transmitter strength. For example, the SKA would enable detection of transmitters with radiated powers comparable to that of terrestrial TV stations over parsec-scale distances. Perhaps of far greater importance is the ability to identify and remove terrestrial radio-frequency

interference, whose diversity in signal structure may be similar to that of ETI signals. The key traits of the SKA for this purpose are the multiple-beaming capabilities from a station along with an array of stations at widely spaced sites.

1.2 Level 2

Transient Followup The SKA will be used to follow up externally-generated triggers of transient events outside the radio regime. A current example of such a program is the followup of gamma-ray burst, searching for afterglows, as triggered by a gamma-ray satellite. Other examples may also become important over the next decade.

Ultra-High Energy Cosmic Rays The SKA should be capable of searching for radio pulses from ultra-high energy cosmic rays (and/or neutrinos) originating either in the Earth's atmosphere or the lunar regolith. It is difficult to identify accelerators for such particles within the local Universe (within the GZK distance, approximately 50 Mpc). The existence of such particles requires either unknown accelerators or new physics.

2 SKA Specifications

In this section we discuss SKA specifications, both as they are baselined and as needed to accomplish the scientific goals described here. In some cases, a baseline specification is not required for all three Level 1 projects. In those cases, we have identified the Level 1 project(s) requiring this specification using RTU to refer to the Radio Transient Universe, PSR for the Galactic pulsar census, and SETI.

$A_{\text{eff}}/T_{\text{sys}}$ The current $A_{\text{eff}}/T_{\text{sys}}$ specification is sufficient to allow detecting 10 times more pulsars in the Galaxy, thereby approaching the goal of detecting most, if not all, of the pulsars in the Galaxy beamed toward us. For the purposes of conducting a thorough yet efficient pulsar survey, a substantial fraction of the array should be in a condensed region so as to provide adequate sensitivity without too large of a beam. Conversely, in order to provide rapid and relatively precise astrometry of newly-detected transients, the SKA must also provide sufficient angular resolution (see below). Initial simulations suggest that the distribution of collecting area should be roughly 50% in a condensed

region for efficient pulsar surveying and roughly 50% on VLBI scales. This specification will also enable the detection over interstellar distances of transmitters whose broadcast powers are comparable to those of terrestrial commercial transmitters. [PSR, SETI]

Frequency Range Minimum frequency range is approximately 0.5 to 15 GHz.

The upper limit on the frequency range is determined by the need to reach 15 GHz to combat interstellar scattering of pulsars toward the Galactic center. A similar upper limit is required to combat self absorption within a transient source. The lower limit on the frequency range is determined by the desire to search for giant pulses from pulsars from at least the Local Group. Assuming that the giant pulses from the Crab pulsar are not the strongest giant pulses produced in the Local Universe, it will be possible to search for giant-pulse producing pulsars in the Virgo Cluster. A similar lower frequency limit is required to search a significant fraction of the Galaxy for pulsars. Finally, approximately one decade of spectral coverage is required to obtain adequate spectral information on newly-detected sources. This frequency range also covers the SETI "waterhole" between 1.4 and 1.7 GHz. [RTU, PSR, SETI]

Field of View (FoV) At least 1° of contiguous sky coverage. This requirement derives from an example straw-man pulsar survey in which the Galactic plane is surveyed with 600 s per pointing. Such a survey, if conducted with 10% of the array time, would be completed in approximately 1 yr. A similar requirement is also derived a straw-man transient survey in which the full sky is surveyed within 1 d, with 5 s per pointing. [RTU, PSR]

Number of Instantaneous FoV The requirement is at least 10 instantaneous FoVs over at least 1 sr. This requirement derives from the desire to monitor multiple sources simultaneously. Without this capability, construction of a pulsar timing array cannot be achieved without unreasonable requirements on telescope time. Moreover, following the temporal and/or spectral evolution of several "active" transients, possibly in conjunction with optical, X-ray, or gamma-ray telescopes is also desired. Finally, for phase referencing during VLBI observations at least 2 pencil beams are desired. This WG allows for using the SKA in a sub-array mode, so not all FoVs require the full collecting area of the SKA. [RTU, PSR, SETI]

Angular Resolution The specified angular resolution of $0.1''$ at 1.4 GHz is *insufficient*. This WG requires approximately 1 mas at 5 GHz based on the need to provide adequate astrometry for parallaxes and followup observations of transient sources as well as to follow source evolution (e.g., within micro-quasars). Instruments at other wavelengths (e.g., NGST) will have an angular resolution of a few tens of milliarcseconds, and the SKA must be able to specify positions at least this well. This angular resolution will also allow for parallaxes to be determined throughout most of the Galaxy and micro-quasars out to the Virgo Cluster. Finally, accurate and rapid distance determination can be used as a means of radio frequency interference mitigation, i.e., establishing transient signals as being celestial. [RTU, PSR, SETI]

Number of Spatial Pixels The requirement of 10^8 spatial pixels is sufficient. This requirement allows for a spatial dynamic range of 10^4 or 1 mas angular resolution over $10''$. This should be sufficient for imaging any possible large scale structure associated with or deriving from a transient source. [RTU]

Surface Brightness Sensitivity This WG has no comment on this requirement.

Instantaneous Bandwidth The requirement of 20% instantaneous bandwidth is sufficient, though less than desirable. This requirement provides adequate sensitivity. An instantaneous bandwidth of 50% would provide both better sensitivity and additional bandwidth for tracking spectral signatures of transients (e.g., dispersion delay or differential arrival times). [RTU, PSR]

CLEAN Beam Dynamic Range The stated requirement of 10^6 is sufficient to enable long (8–12 hr) integrations. [RTU, PSR, SETI]

Polarization Purity The stated requirement of -40 dB is sufficient for on-source observations, in short integrations (e.g., “snapshots”). Indeed, given that some classes of transients have or may have high levels of polarization (e.g., radio pulsars and exoplanets), high polarization purity may enable the detection of transients at lower flux density levels that would otherwise be possible. However, for off-source observations, i.e., detecting the polarization of a weakly polarized source in the field with a typical “strong” polarized source also in the field, it is insufficient. In order to approach the thermal noise limit in a long

integration (e.g., 12 hr), the requirement is that of the total intensity requirement, i.e. -60 dB. [RTU, SETI]

3 Additional SKA Requirements

This WG also has a number of other requirements that are not addressed by the current specifications.

Correlator The correlator must be able to produce, for all baselines, a channel bandwidth of $0.2 \text{ MHz}(\nu/1 \text{ GHz})^{-3}$ over a total bandwidth of 400 MHz. This requirement allows correction for dispersion smearing from pulsar pulses (and Type I/II stellar flares) to acceptable levels. This requirement is equivalent to 2048 channels. [RTU, PSR, SETI]

Dump Time The system must be able to produce a time series with a sampling resolution of approximately $50 \mu\text{s}$ for a pulsar search mode and approximately $5 \mu\text{s}$ for a pulsar timing mode. For the pulsar timing mode, the sampling need not be output from the correlator but from (the roughly) 10 phased-array beams. [PSR]

Acquisition Time The SKA should be capable of accommodating non-SKA triggers of transient events (e.g., from an X- or gamma-ray satellite). Ideally, this WG would like (a sub-array of) the SKA to be capable of responding to an external trigger anywhere in the sky within roughly 1 s. At worst, the SKA should have an acquisition time no worse than that of any current radio-astronomical instrument, e.g., $20^\circ \text{ min.}^{-1}$. [RTU]

Transient Buffer The signal from (at least a fraction of) the SKA should be stored in a transient buffer so the SKA could be phased up in a specified direction in order to respond to an internal (and possibly external) trigger. [RTU]

4 Exploring the Transient Radio Sky with the SKA

In this section we sketch how the SKA might be used to explore the transient radio sky. Our proposed observations exploit the multi-beaming capability of the SKA to monitor sources known or expected to show transient or highly variable radio emission as well as to search for hypothesized classes

of sources in a far more unbiased manner than has been possible previously. We discuss the various search programs separately.

All-Sky Survey: We propose a Radio Transient All-Sky Survey (RTASS) that would survey initially large swaths of solid angle by using *sub-arrays* of the SKA. Signals from different stations will be combined through statistical tests to discriminate between short-time scale terrestrial and celestial radio emission. In this mode the full gain of the SKA would be partitioned. Radio emission identified as being celestial in origin will then be targeted with an SKA beam having the full gain of the array.

High-Energy Source Follow-up We propose to devote one SKA beam to follow-up observations of sources detected by high-energy telescopes. The exemplar of the class of source being targeted is a gamma-ray burst. The potential rapid, electronic beam steering provided by the SKA allows for essentially instantaneous follow-up of a source detected by a gamma-ray, X-ray, or neutrino telescope. Radio follow-up observations are particularly useful as only radio wavelengths can penetrate highly obscured regions. This is demonstrated in the case of gamma-ray bursts where the progenitors of the burst are likely to be located in such regions.

Radio Monitoring We propose to devote one SKA beam to a monitoring program of known classes of transient or highly variable radio sources for which the onset of the activity is random. The prototypes of this kind of program are the US Navy and NASA monitoring programs for extreme scattering events and radio counterparts to X-ray binaries, respectively, on the NRAO Green Bank Interferometer (GBI) in the early and mid-1990s. In contrast to the limited sensitivity of the GBI, however, the SKA offers the possibility of monitoring an order of magnitude more sources.

SETI We propose to devote one SKA beam to a survey for artificial radio emission from the nearest 1000 stars. This program is modelled on the SETI Institute's Project Phoenix, but the far greater sensitivity afforded by the SKA means that transmitters with radiated power comparable to terrestrial TV stations should be detectable. Other, blind SETI surveys would be conducted along with deep pulsar surveys of the Milky Way (see below), surveys for high-Galactic-latitude pulsars, and deep surveys for galaxies.

5 Radio Pulsar Science with the SKA

Searching for pulsars to approach a full Galactic census, such as that displayed in Figure 1, will yield a cornucopia that includes the ability to model the Galaxy in exquisite detail, identify the evolutionary paths in the formation of compact objects, and the exploitation of pulsars for testing fundamental physics. Specific activities in pulsar science will include:

Galactic Pulsar Surveys: Pulsars of different types have somewhat different spatial distributions and the SKA can be used in optimized modes to achieve full censuses of canonical magnetic-field pulsars, millisecond pulsars, and binary pulsars with white dwarf, neutron star and black-hole companions. Evolutionary paths for these and other objects, including magnetars and the postulated strange stars can be determined or constrained. Binaries with both large and small orbital periods, including those undergoing spiral-in from losses to gravitational radiation, will serve as important laboratories for stellar evolution and relativity. Many objects will be prime targets for gravitational wave detectors.

Extragalactic Pulsars: With the SKA, periodicity searches can reach to at least 1 Mpc, encompassing a volume that includes several large galaxies (M31 and M33) as well as scores of dwarf galaxies. Giant pulse searches, already mentioned in the transients section, could reach to at least 5 Mpc and most likely could be pushed to the Virgo cluster of galaxies. The multiple beaming/multiple site aspect of the SKA is essential for identification of dispersed pulses on intergalactic distances. Observing the pulsar population in a wide variety of external galaxies allows studies of the star formation rate of massive stars, via their end-products. Detected signals are ideal for probing the magneto-ionic media in the host galaxies and in the intergalactic medium.

Galactic Tomography With a full pulsar sample, line of sight measures including the dispersion measure, rotation measure and scattering measure, can be deconstructed into high-precision 3D models of the local mean electron density, the level of small-scale fluctuation in electron density, and the mean and fluctuating magnetic field. For the first time, detailed correlations with other probes of Galactic structure can be made and an understanding can be achieved of cosmic ray sources and how cosmic rays propagate.

Probing Fundamental Physics: The SKA Galactic Census will provide a large number (~ 1000) of spun-up millisecond pulsars. Establishing the lower period limit sets important constraints on the Equation-of-State, enabling a deeper understanding of condensed matter with densities of about $10^{14} \text{ g cm}^{-3}$. The vast majority of millisecond pulsars will be found in binary systems, resulting in a large number of neutron star mass measurements. It will be possible to exclude alternative theories of gravity, and the increase over the currently small number of double neutron star systems will allow the study of gravitational effects in the strong field limit with unique precision. Pulsar-Pulsar systems are likely to be discovered, promising massively over-determined test systems. A discovery of black-hole pulsar systems enables to measure frame dragging effects as well as black hole properties such as spin and quadrupole moment.

Pulsar Timing Array: A large number of isotropically distributed millisecond pulsars on the sky will act as multiple arms of a cosmic gravitational wave detector. The SKA is therefore an instrument to measure low-frequency gravitational waves in a regime inaccessible to detectors such as LIGO, GEO600, or LISA. The SKA offers the opportunity to discover gravitational waves produced by the merger of massive black holes or waves of cosmological origin as predicted by a number of cosmology models. At the same time, the observations can be used to explore the possibilities to use the pulsar array as a new highly precise time standard.

High-precision Astrometry: In addition to the astrometrical capabilities of the SKA in the suggested configuration, timing observations with the SKA will also provide high precision distances and proper motion for a large number of millisecond pulsars throughout the Galaxy and in globular clusters. Often these measurements will surpass the precision that will be obtainable with optical missions like GAIA or SIM. Position measurements of pulsars can be used to tie the Earth-orbit oriented solar system reference frame to the quasi-inertial Earth-spin oriented extragalactic reference frame with unprecedented accuracy. Proper motion measurements of young pulsars will provide information about the birth velocities of pulsars and therefore insight in core collapse physics.

Probing Local Environment: Pulsars observed with the SKA are superb probe to study their local surrounding. The measurement of apparent

period derivatives of millisecond pulsars can be used to study the local gravitational potential, not only supplementing our knowledge about the Galaxy, but also enabling the study of gas concentration, mass distribution and dynamics in globular clusters. Measuring polarisation properties of pulsars with interacting companions provides information about properties, evolution and winds of these companions.

The Shapes of Pulsar Beams With the high gain of the SKA, the detailed shapes of pulsar pulses can be determined to many orders of magnitude below the pulse peaks. Such information is crucial for understanding the mechanism of pulsar beaming (relativistic beaming vs. collimated particle jets) and determining the pulsar birth rate. A monitoring program with the SKA can trigger observations which allow to resolve pulsar magnetospheres using interstellar scintillation. An emission region of probably tens to a few hundreds km across can be studied in a distance of a few thousand light years or more.

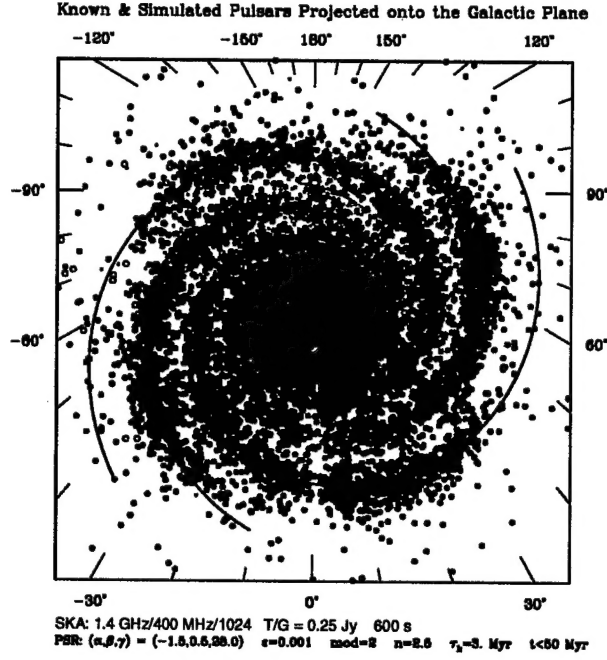


Figure 1: Projection onto the Galactic plane of a simulated SKA survey at 1.4 GHz for pulsars. The blue dots show the number of pulsars detected by the SKA ($\sim 10^4$), assuming 1024 channels across a 400 MHz with a 600 s integration time per pointing. The open circles and black dots show known pulsars from the Parkes Multibeam survey and Princeton catalog, respectively. Also shown are the spiral arms as defined in the Cordes-Lazio electron density model (Cordes & Lazio 2002, in preparation). In the simulation, pulsars are born preferentially in spiral arms but move away from the arms and from the galactic plane according to a velocity distribution consistent with that of known radio pulsars.